Supporting Data for Integrated Duty Cycle Test Method – Results from Stove 7 Testing

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BACKGROUND

Although wood-burning devices provide a small portion of the energy used in residences in the United States, those devices are a substantial source of air pollutant emissions. In 2017, residential wood-burning devices in New York State were responsible for 51% of fine particulate matter ($PM_{2.5}$) and 69% of volatile organic compound (VOC) emissions from all stationary fuel combustion sources in the State. (US EPA 2017) $PM_{2.5}$ and other wood smoke constituents are linked to a range of respiratory, cardiac, and neurological health effects, as well as increased mortality. (Naeher, 2007) Nationally, residential wood smoke accounts for 20% of total stationary and mobile polycyclic organic matter (POM) emissions, 50% of all area source air toxic cancer risks, and 8% of the overall noncancer (respiratory) risk. (NATA 2011)

Wood stoves that perform well in the laboratory but produce much higher emissions in the field pose a risk to public health for users and nearby and downwind communities. This report documents an investigation of the factors that affect emissions from wood-burning devices and the development of laboratory certification test procedures that better reflect in-field performance of these appliances than the current test methods. Improved emission certification test protocols would promote the design and manufacture of cleaner-burning and more efficient residential wood-burning devices.

The United States Environmental Protection Agency's (EPA's) New Source Performance Standards (NSPS) for Residential Wood Heaters limit emissions of particulate matter (PM) from new wood-fired residential heaters. A wood heater model is certified as compliant with the NSPS requirements if emissions from a prototype appliance, as measured by an EPA-qualified testing laboratory, are consistent with those limits.

The current federal reference certification method for wood stoves, EPA's Method 28R (M28) crib wood test, is a "hot to hot" steady-state test that burns a specified configuration of dimensional Douglas fir lumber with spacers. M28 builds on ASTM[1] Method 2780, which incorporated EPA's original Method 28 with some modifications. Because M28 does not replicate typical consumer fueling and operating conditions and does not record emissions during startup periods, the certification results do not accurately represent in-use emissions.

ASTM has since developed a cordwood stove test method. The EPA has designated that method, ASTM 3053-17, as a Broadly Applicable Alternative Test Method (ATM) procedure for certifying compliance with the NSPS emissions standards. However, many of the problems in the M28 are not addressed in the ASTM 3053-17 procedure, which measures the stove's average performance across long steady-state burns. The ASTM 3053-17 test provides limited information about emissions that occur during cold-

[1] ASTM, International, formerly known as the American Society for Testing and Materials.

starts, fuel reloads, and the end phases of stove operation. In addition, those procedures do not generate replicate data that would allow for an assessment of the reproducibility of results.

Emissions from wood-burning devices are far more variable than those produced by appliances that burn other fuels. Natural gas and heating oil are homogeneous fuels with consistent physical and chemical parameters. By contrast, the wood burned in residential wood heaters is highly heterogeneous, encompassing a range of species, moisture contents, piece sizes, densities, and bark and resin contents. Gas and oil fuels are mechanically fed to the heating appliances. Cordwood stoves are filled by the user, which introduces significant variability in burn characteristics. Further, operators control door position, airflow, and other settings that affect stove performance and emissions. An effective emission certification test procedure must include elements and approaches that capture and measure this inherent variability.

It is not possible to test the full range of homeowner stove use patterns. A 2019 study found that homeowner use patterns varied widely across appliances and even within the same home over a month-to-month or year-to-year period. (Ahmadi 2019). Because achieving a "real-world" test is not feasible, a more effective approach is to assess an appliance's operation over variable conditions. To accurately represent stove performance in the field, a certification test must account for in-use variability in fueling and operating parameters while providing sufficient specificity to allow the results to be reproducible and to allow comparisons between models. The Northeast States for Coordinated Air Use Management (NESCAUM) collaborated with various partners to develop new test methods for stoves and central heating units that fulfill those criteria. Collectively, these protocols are known as the Integrated Duty Cycle (IDC) test methods.

The IDC methods are designed to be accurate, representative of in-use conditions, repeatable and affordable, and address many of the shortcomings identified with the EPA, ASTM, and Canadian Standards Association (CSA) test methods. The IDC protocol: (1) characterizes variability with greater precision than current methods; (2) captures representative operations, including startup, reload periods, and a variety of heat loads; (3) includes simpler and more accurate PM measurement approaches; (4) better measures efficiency; and (5) reduces the time to conduct certification tests. The single-day test allows for replicate testing without appreciably increasing certification test costs. It also provides a framework that can be easily adjusted if knowledge changes require changes to the protocols.

This report presents data on the final round of IDC testing on one cordwood stove to highlight that low emissions performance can be achieved using the IDC Stove Protocol, making it suitable for use as an Alternative Test Method under the current regulatory schema. This effort aims to inform the development of the next generation test method protocols that will promote the design and identification of low emissions, high-efficiency cordwood stoves.

To obtain data for this effort, NESCAUM of Boston, Massachusetts, contracted with Hearth Lab Solutions (HLS) of Bethel, VT. HLS conducted research to obtain data to inform the development of the Integrated Duty Cycle (IDC) test method for cordwood stoves. All testing information contained in this report was obtained at the HLS Laboratory located in Bethel, Vermont. HLS technicians performed all

stove operations and filter testing. HLS technicians managed TEOM instrumentation and filter changes. NESCAUM staff managed TEOM operations and conducted data processing activities.

HLS is a research lab that operated under a Quality Assurance Program Plan for this project. It is not an EPA-approved certification lab. The data collected under this project was not collected as part of a certification regime and is not meant to provide data to certify appliances. It was developed as part of a research project to develop the IDC protocol. As such, the final operational and fueling elements were used to conduct the testing, but the complete and final protocol was not developed until after completing the testing portion of the project. Protocol development took place after final data was obtained to ensure that the IDC Stove Protocol could be run successfully on a wide variety of appliances. The final task in the project was the completion of a full protocol sufficient for use in a regulatory setting. As part of the protocol development process, additional reporting elements were added to the protocol after the testing to enhance compliance assurance oversight efforts.

At the conclusion of the protocol development process, Alaska submitted a request to US EPA to accept this protocol as an Alternative Test Method (ATM). Alaska's state regulations reference the use of the IDC Stove protocol. In obtaining approval as a federal ATM, companies could use the protocol to demonstrate compliance with federal and Alaska standards. This ATM is separate from the research protocol currently in use by EPA and posted in the EPA docket. The ATM contains requirements relevant to the current federal regulation, while the Research Protocol assumes use under a new regulatory construct.

APPLIANCE SPECIFICATIONS

Appliances used for the initial research were subject to a non-disclosure agreement (NDA) with HLS. This NDA requires that no data or materials shall be submitted to NESCAUM or NYSERDA that include or could identify model/manufacturer information used for testing. Therefore no data in this report can be provided that would violate the terms of the NDA. The NDA does allow disclosure of the emission control type, construction material, firebox size and loading parameter. The stove discussed in this report is a high mass stove with a firebox volume of 1.9 ft^3. It uses both catalytic and non-catalytic controls.

TEST AND APPLIANCE LOCATION INFORMATION

- Appliance Tested: *cannot disclose, NDA applies*
- Serial Number: *cannot disclose, NDA applies*
- Manufacturer*:* *cannot disclose, NDA applies*
- Catalyst: Yes
- Heat exchange blower: No
- Type: Cordwood Stove – variable air settings
- Style: Freestanding
- Date Received: 12/23/2020
- Test Method: IDC Stove Protocol – protocols from 2018, 2019, and 2020
- Test Fuel Species Maple and Oak
- Testing Period – Start: July 2018
- Testing Period – End April 2020
- Test Location: Hearth Lab Solutions Laboratory
  62 Vermont Castings Way, Bethel, VT
- Elevation: 550’ above sea level
- Test Technician(s): Mark Champion
- Observers: none

TEST PROCEDURE AND EQUIPMENT

TEST PROCEDURE

The data in this report reflects data acquired to develop the final protocol. The framework for the testing approach was completed prior to drafting a complete protocol. Testing that occurred in July 2018 was guided by the May 2018 IDC Stove framework, which can be found in Attachment A. HLS obtained TEOM measurements from a 1400 TEOM. TEOM data acquition was guided by the 1400 TEOM SOP, which can be found in Attachment B. IDC Stove testing in 2019 was guided by a refined draft protocol, which can be found in Attachment C. HLS obtained TEOM measurements from a 1405 TEOM. TEOM data acquition was guided by the 1405 TEOM SOP, which can be found in Attachment D. All TEOM SOPs, operation, and fueling protocols are the property of NYSERDA and are provided in this report with their permission. These protocols cannot be cited, copied, distributed, or modified without the written permission of NYSERDA.

APPLIANCE & EQUIPMENT OPERATION

Mark Champion of HLS completed all operations related to the stove's operation and fueling. Mark Champion also conducted all sampling and measurements related to the filter data. Mark Champion completed filter changes on the TEOM to obtain real-time PM measurements. George Allen oversaw the operation of the TEOM remotely.

Mark Champion, George Allen, Dr. Mahdi Ahmadi, and Barbara Morin performed analytical procedures and data analysis.

Data acquisition at HLS followed the QAPP provided in Attachment F. This attachment also includes information on specific equipment used at the HLS facility.

TEOM PM Emission Instrumentation

The research testing obtained both real-time PM data and filter data. Filter data used ASTM 2515 procedures. Real-time PM data used a Tapered Element Oscillating Microbalance (TEOM). Testing that took place prior to October 2018 used the TEOM Thermo Scientific 1400. Standard Operating Procedures for the TEOM 1400 Thermo Scientific are contained in Attachment B. The TEOM SOP is the property of NYSERDA and cannot be used, modified, or copied without their permission. We have received their permission to include the SOP in this report. After October 2018, HLS used a 1405 Thermo Scientific TEOM. This TEOM SOP is the property of NYSERDA and cannot be used, modified, or copied without

their permission. We have received their permission to include the SOP in this report. The 1405 SOP can found in Attachment D.

TEST CONDITIONS SUMMARY

TEST FUEL PROPERTIES

All HLS cordwood fuel is purchased locally within the state of Vermont. Wood arrives in log or split wood form and then is organized according to species and size. Wood with rot or other evidence affecting quality is removed from fuel selection and is not used in testing.

Wood is stored indoors where the minimum storage temperature 24 hours within testing is 60˚F. Wood is air-dried at room temperatures. If needed to maintain moisture content, there is a humidity-controlled environment at HLS.

The amount of bark on wood that arrives at the lab in log and or split form varies. Bark may also fall off during seasoning or handling of fuel. The bark is never intentionally removed from the cordwood. However, due to the slow air-drying process, bark typically remains on the fuel pieces. A small chunk or gash may be removed when needed to bring a piece into weight specification, but the entire or majority of bark, if present, is not touched. Cordwood for the test was prepared within 24 hours of testing. The prepared cordwood was then weighed and measured for moisture content within 2-3 hours from the start of each test day. The following section provides information on fuel loads.

For all test runs, preparation of the fuel was guided by the IDC Stove Calculator version 1. Data outputs from the calculator including individual piece weights, moisture measurements, and load volumes can be found in Attachment G. Please note that the spreadsheet data in these files use the original nomenclature for the four phases of the IDC. The table below provides a crosswalk between the headings used in the research spreadsheets and the load names in the protocol available as an ATM.

Table 1. Load Terms Crosswalk ATM-140 and Fuel Calculator

Alt-140 Phase Title	Spreadsheet Phase Title	Load Characteristics
L1	Start-up	1 lb/ft^3 kindling and 3 lb/ft^3 starter
L2	High	7 lb/ft^3 small pieces
L3	Medium	5 lb/ft^3 large pieces. Target=2 pieces
L4	Low	12 lb/ft^3 kindling mix of large and small pieces

LAB CONDITIONS

The wood stove filter measurements were tested in accordance with the ASTM E2515. Particulate emissions were measured using sampling trains consisting of two filters (front and back). The appliance was tested for thermal efficiency and carbon monoxide (CO) emissions in accordance with CSA B415.1-10.

Sampling Locations

The dilution tunnel is 6 inches in diameter. Sample ports are located 5.75 feet downstream from any disturbances and 1.6 ft upstream from any disturbances. The dilution tunnel hood is 2.0 ft in diameter. Testing schematic and photos can be found in Attachment H. The following tables summarize the lab conditions during testing. Table 2 summarizes lab conditions during testing.

Table 2. Lab Conditions

Run #	Room Temperature		Barometric Pressure		Relative Humidity	
	Before	After	Before	After	Before	After
	F	*F*	*In Hg*	*In Hg*	*%*	*%*
1	*77*	*77*	*29.41*	*29.30*	*62%*	*79%*
2	*74*	*77*	*29.20*	*29.26*	*79%*	*84%*
3	*73*	*78*	*29.36*	*29.35*	*84%*	*81%*
4	*55*	*60*	*29.62*	*29.62*	*73%*	*39%*
1	*72*	*68*	*29.27*	*29.36*	*62%*	*27%*
2	*66*	*69*	*29.60*	*29.77*	*30%*	*28%*
3	*64*	*67*	*29.86*	*29.66*	*31%*	*59%*

Table 3. Test Run Conditions

Run#	***Run time***	***Train Precision***	**Avg dilution tunnel measurements**			
			Average Tunnel Flow	***Minimum Tunnel Flow***	***Max Tunnel Temp***	***Max DP***
	Minutes	*%*	*CFM*	*CFM*	*F*	
1	672	1.2	200		132	0.085
2	647	6.0	203		135	0.084
3	661	0.8	201		135	0.086
4	619	1.0	231		100	0.102
1	669	2.9	200		133	0.091
2	657	1.2	200		123	0.082
3	638	0.8	201		123	0.096

SUMMARY TABLES

Table 4 summarizes data that can be released about the appliance without vilating the terms of the NDA.

Table 4. Model Identification

Model Name/number	Stove 7 – NDA
Manufacturer	NDA
Manufacturer address	NDA
Appliance category	NDA
Usable Firebox Volume	1.9
Catalytic	Yes
Convection Air Fan	No

Table 5 summarizes the information about the lab.

Table 5. Laboratory Information

Testing Lab	Hearth Lab Solutions
Address	62 Vermont Castings Way; Bethel, VT
ISO Accreditation info	None
Testing dates	July 25, 2018 through April 29, 2020
Test Method	IDC Draft Protocol ASTM E2515
Dilution Tunnel Inside Diameter in inches	6”
Filter diameter	47 mm
Filter material	Pallflex Emfab filters are made of borosilicate glass microfibers that are reinforced with woven glass cloth and bonded with PTFE.

Table 6. Summary Results – Maple.

Date	Run #	Filter Data				TEOM	Test Time (min)	CO* (g/kg)	Efficiency
		PM Train 1 (g/hr.)	PM Train 2 (g/hr.)	PM (g/hr.)	PM Train Prec. (%)	PM (g/hr)			
7/25/18	1	2.8	2.9	2.8	1.2	2.00	672	34	70.2
7/26/18	2	2.1	2.4	2.3	6.0	1.66	647	30	70.2
7/27/18	3	2.0	2.0	2.0	0.8	1.23	661	29	71.3
4/29/20	4	1.6	1.5	1.5	1.0	0.80	619	17	NA
Average		***2.13***	***2.20***	***2.15***	***NA***	***1.42***	***650***	***27.5***	***70.6%***

Table 7. Summary Results – Oak

Date	Run #	Filter Data				TEOM	Test Time (min)	CO* (g/kg)	Efficiency
		PM Train 1 (g/hr.)	PM Train 2 (g/hr.)	PM (g/hr.)	PM Train Prec. (%)	PM (g/hr)			
4/3/19	1	1.4	1.3	1.4	2.9	1.01	669	23	69.2
4/4/19	2	3.2	3.3	3.3	1.2	2.50	657	25	67.8
4/5/19	3	1.9	1.9	1.9	0.8	1.20	638	19	69.5
Average		***2.167***	***2.167***	***2.2***		***1.6***	***655***	***22.3***	***68.8***

TEST RUN NARRATIVE

Detailed information for each run can be found in Attachment I. Computer notes are contained in Attachment I, handwritten notes to include filter weights are contained in Attachment J.

Maple Run #1

The first maple run was performed on July 25, 2018. The test was performed on Test Stand B.

Load 1-Start-Up

The startup fuel configuration used a top down fuel load configuration. L1, the startup load weighed 7.56 pounds – 1.89 pounds of kindling and 5.67 pounds of starter fuel. Fuel load density was 0.99 lb/ft^3 for kindling and 2.98 lb/ft^3 for starter fuel pieces. Emissions sampling began from a cold start ignition at

9:22. It took less than 60 seconds to ignite the fuel. The appliance door was cracked, the bypass was open, and all air settings were fully open. The appliance door was closed 9:25. Yellow flame was lost at 9:35, to re-engage the fire, the door was cracked open at 9:35 and remained open until 9:44. At 9:57 (35 minutes into the test), a fuel adjust occurred. The first phase ended when 5.6 pounds of fuel was burned. This left a coal bed weight of 1.9 pounds (14% of the second load fuel weight). Total time to complete Load 1 was 56 minutes. The overall HHV heating efficiency during this phase was 58.81%, the combustion efficiency was 96.43%, and the heat transfer efficiency was 60.98%. The heat input was 56,358 Btu/hr, and heat output was 33,142 Btu/hr.

Load 2 (High)

Fifty-six minutes into the test, the door was opened and the 7.04 lb/ft^3 load of small pieces was added. Four pieces of fuel were added that combined had a total fuel load weight was 13.38 pounds. The appliance door was immediately shut and the air settings remained fully open and the bypass was closed. A fuel adjust occurred 65 minutes into the test. The appliance air setting was moved to fully closed at minute 108 when 50% (6.7 pounds) of the second fuel load had been consumed. The second phase ended when 12.08 (90%) pounds of fuel was burned. Total time to complete Load 2 was 143 minutes, total elapsed test time 199 minutes. The coal bed weight at the end of the phase was 3.2 pounds. The overall HHV heating efficiency during this phase was 67.08%, the combustion efficiency was 97.74%, and the heat transfer efficiency was 68.63%. The heat input was 43,833 Btu/hr, and the heat output was 29,404 Btu/hr.

Load 3 (Medium/Maintenance)

One-hundred and ninety-nine minutes into the test the door was opened and two fuel pieces for the 5.00 lb/ft^3 load of large pieces were loaded into the appliance. The bypass was open for the fuel loading event. The door was closed immediately after loading and the bypass was closed. Air settings remained at low during this phase. The third phase ended when 8.5 (89%) pounds of fuel was burned. Total time to complete Load 3 was 158 minutes, total elapsed test time 357 minutes. The coal bed weight at the end of the phase was 4.2 pounds. The overall HHV heating efficiency during this phase was 74.28%, the combustion efficiency was 98.68%, and the heat transfer efficiency was 75.27%. The heat input was 32,635 Btu/hr, and the heat output was 24,240 Btu/hr.

Load 4 (Low)

Three-hundred and fifty-seven minutes into the test the final fuel load (11.77 lb/ft^3 load density) consisting of three large pieces and two small pieces was placed in the appliance. Fuel for this load was added from largest to smallest piece. Due to the size of the coal bed, one piece, the smallest piece, from the final fuel load would not fit in the appliance. Immediately after loading the fuel, air settings were moved to the fully open position, door and bypass were closed immediately. At minute 366 air settings were moved to the fully closed position. No fuel adjusts occurred during this phase. The fourth phase ended when 20.17 (90%) pounds of fuel was burned. Total time to complete Load 4 was 315 minutes, total elapsed test time 672 minutes. The coal bed weight at the end of the phase was 6.4 pounds. The overall HHV heating efficiency during this phase was 70.36%, the combustion efficiency was 95.82%,

and the heat transfer efficiency was 73.43%. The heat input was 34,553 Btu/hr, and the heat output was 24,310 Btu/hr.

Maple Run #2

The second maple run was performed on July 26, 2018. The test was performed on Test Stand B.

Load 1-Start-Up

The startup fuel configuration used a top down fuel load configuration. L1, the startup load weighed 7.6 pounds – 1.9 pounds of kindling and 5.7 pounds of starter fuel. Fuel load density was 1 lb/ft^3 for kindling and 3 lb/ft^3 for starter fuel pieces. Emissions sampling began from a cold start ignition at 9:24. It took less than 60 seconds to ignite the fuel. The appliance door was cracked, the bypass was open, and all air settings were fully open. The appliance door was closed 9:29. No poking, stirring events, or fuel adjustments were made during this phase of the test. The first phase ended when 5.6 pounds of fuel was burned. This left a coal bed weight of 2.0 pounds (75% of the fuel load, and 15% of the second load fuel weight). Total time to complete Load 1 was 45 minutes. The overall HHV heating efficiency during this phase was 59.21%, the combustion efficiency was 97.20%, and the heat transfer efficiency was 60.91%. The heat input was 72,108 Btu/hr, and heat output was 42,693 Btu/hr.

Load 2 (High)

Forty-five minutes into the test, the door was opened and the 6.99 lb/ft^3 load of small pieces were added. Four pieces of fuel were added that combined had a total fuel load weight was 13.38 pounds. The appliance door was immediately shut and the air settings remained fully open and the bypass was closed. The appliance air setting was moved to fully closed at minute 99 when 50% (6.7 pounds) of the second fuel load had been consumed. The second phase ended when 11.99 (90%) pounds of fuel was burned. Total time to complete Load 2 was 141 minutes, total elapsed test time 186 minutes. The coal bed weight at the end of the phase was 3.3 pounds. The overall HHV heating efficiency during this phase was 67.02%, the combustion efficiency was 98.45%, and the heat transfer efficiency was 68.08%. The heat input was 44,680 Btu/hr, and the heat output was 29,946 Btu/hr.

Load 3 (Medium/Maintenance)

One-hundred and eighty-six minutes into the test the door was opened and two fuel pieces for the 4.99 lb/ft^3 load of large pieces were loaded into the appliance. The bypass was open for the fuel loading event. The door was closed immediately after loading and the bypass was closed. Air settings remained at low during this phase. The third phase ended when 8.6 (91%) pounds of fuel was burned. Total time to complete Load 3 was 178 minutes, total elapsed test time 364 minutes. The coal bed weight at the end of the phase was 4.2 pounds. The overall HHV heating efficiency during this phase was 74.36%, the combustion efficiency was 98.75%, and the heat transfer efficiency was 75.30%. The heat input was 29,185 Btu/hr, and the heat output was 21,702 Btu/hr.

Load 4 (Low)

Three-hundred and sixty-four minutes into the test the final fuel load consisting of three large pieces and one small piece was placed in the appliance. A second small piece was prepared for this phase but could not be placed in the firebox. Fuel for this load was added from largest to smallest piece. Due to the size of the coal bed, one piece, the smallest piece, from the final fuel load would not fit in the appliance. A fuel load with a loading density of 12 lb/ft^3 was prepared but the actual fuel loading density was 10.21 lb/ft^3 due to removal of the single fuel piece. The door was cracked open and the bypass was open for the first five minutes of this phase. At minute 367 the bypass was closed. At minute 368 the door was closed. Air settings were placed in the fully open position for the first ten minutes of the test phase. At minute 373 air settings were placed in the fully closed position. No fuel adjusts occurred during this phase. The fourth phase ended when 17.49 (90%) pounds of fuel was burned. Total time to complete Load 4 was 283 minutes, total elapsed test time 647 minutes. The coal bed weight at the end of the phase was 6.1 pounds. The overall HHV heating efficiency during this phase was 70.41%, the combustion efficiency was 96.35%, and the heat transfer efficiency was 73.08%. The heat input was 34,233 Btu/hr, and the heat output was 24,104 Btu/hr. During this phase Train 1 experienced a one-minute filter temperature of 225F.

Maple Run #3

The third maple run was performed on July 27, 2018. The test was performed on Test Stand B.

Load 1-Start-Up

The startup fuel configuration used a top down fuel load configuration. L1, the startup load weighed 7.59 pounds – 1.89 pounds of kindling and 5.7 pounds of starter fuel. Fuel load density was 0.99 lb/ft^3 for kindling and 3.00 lb/ft^3 for starter fuel pieces. Emissions sampling began from a cold start ignition at 9:10. It took less than 60 seconds to ignite the fuel. The appliance door was cracked, the bypass was open, and all air settings were fully open. The appliance door was closed at minute 5. No poking, stirring events, or fuel adjustments were made during this phase of the test. The first phase ended when 5.6 pounds of fuel was burned. This left a coal bed weight of 2.0 pounds (74% of the fuel load, and 15% of the second load fuel weight). Total time to complete Load 1 was 46 minutes. The overall HHV heating efficiency during this phase was 62.45%, the combustion efficiency was 98.91%, and the heat transfer efficiency was 63.15%. The heat input was 68,876 Btu/hr, and heat output was 43,016 Btu/hr.

Load 2 (High)

Forty-six minutes into the test, the door was opened and the 7.02 lb/ft^3 load of small pieces were added. Four pieces of fuel were added that combined had a total fuel load weight was 13.33 pounds. The appliance door was immediately shut and the air settings remained fully open and the bypass was closed. The appliance air setting was moved to fully closed at minute 89 when 50% (6.7 pounds) of the second fuel load had been consumed. The second phase ended when 12.03 (90%) pounds of fuel was burned. At minute 187 a fuel adjust was completed to maintain combustion. Total time to complete Load 2 was 153 minutes, total elapsed test time 199 minutes. The coal bed weight at the end of the phase was 3.3 pounds. The overall HHV heating efficiency during this phase was 69.30%, the combustion efficiency was 98.61%, and the heat transfer efficiency was 70.28%. The heat input was 41,573 Btu/hr, and the heat

output was 28,812 Btu/hr. It should be noted that modifications to the data were made for the first three minutes of the start-up phase. These modifications were needed because the CO and CO2 data for the first few minutes of the load combustion are very low (close to zero) and in the SLM efficiency calculations this creates a false condition of super perfect combustion. The SLM method is very sensitive particularly to CO readings. To address this issue, manual changes to the CO and CO2 readings were made for the the first three minutes. They were modified by equating them to the closest normal value.

Load 3 (Medium/Maintenance)

One-hundred and ninety-nine minutes into the test the door was opened and two fuel pieces for the 4.91 lb/ft^3 load of large pieces were loaded into the appliance. The bypass was open for the fuel loading event. The door was closed immediately after loading and the bypass was closed. Air settings remained at low during this phase. At minute 340, a yellow flame was no longer visible so a fuel adjust and rake were completed. The third phase ended when 8.7 (94%) pounds of fuel was burned. This load consumed 4% more than the target for this phase. Total time to complete Load 3 was 146 minutes, total elapsed test time 345 minutes. The coal bed weight at the end of the phase was 3.9 pounds. The overall HHV heating efficiency during this phase was 75.68%, the combustion efficiency was 98.84%, and the heat transfer efficiency was 76.58%. The heat input was 37,410 Btu/hr, and the heat output was 28,313 Btu/hr.

Load 4 (Low)

Three-hundred and forty-five minutes into the test the final fuel load consisting of three large pieces and two small pieces were placed in the appliance. A third small piece was prepared for this phase but could not be placed in the firebox. Fuel for this load was added from largest to smallest piece. Due to the size of the coal bed, one piece, the smallest piece, from the final fuel load would not fit in the appliance. A fuel load with a loading density of 12 lb/ft^3 was prepared but the actual fuel loading density was 10.36 lb/ft^3 due to removal of the single fuel piece. The door was cracked open and the bypass was open for the first five minutes of this phase. At minute 349 the bypass and door were closed. Air settings were placed in the fully open position for the first ten minutes of the test phase. At minute 355 air settings were placed in the fully closed position. No fuel adjusts occurred during this phase. The fourth phase ended when 17.69 (90%) pounds of fuel was burned. Total time to complete Load 4 was 315 minutes, total elapsed test time 661 minutes. The coal bed weight at the end of the phase was 5.9 pounds. The overall HHV heating efficiency during this phase was 69.95%, the combustion efficiency was 95.66%, and the heat transfer efficiency was 73.12%. The heat input was 30,414 Btu/hr, and the heat output was 21,275 Btu/hr.

Maple Run #4

The fourth maple run was performed on April 29, 2020 to obtain additional data given the missed target for reloading that occurred on Run #2. The test was performed on Test Stand B.

Load 1-Start-Up

The startup fuel configuration used a top down fuel load configuration. L1, the startup load weighed 7.44 pounds – 1.94 pounds of kindling and 5.5 pounds of starter fuel. Fuel load density was 1.02 lb/ft^3 for

kindling and 2.89 lb/ft^3 for starter fuel pieces. Emissions sampling began from a cold start ignition at 8:39. It took less than 60 seconds to ignite the fuel. The appliance door was cracked, the bypass was open, and all air settings were fully open. The appliance door was closed at minute 4. Bypass was closed at minute 15. No poking, stirring events, or fuel adjustments were made during this phase of the test. The first phase ended when 5.44 pounds of fuel was burned. This left a coal bed weight of 2.0 pounds (73% of the fuel load, and 15% of the second load fuel weight). Total time to complete Load 1 was 50 minutes. The overall HHV heating efficiency during this phase was 70.09%, the combustion efficiency was 98.03%, and the heat transfer efficiency was 71.50%. The heat input was 37,384 Btu/hr, and heat output was 26,203 Btu/hr.

Load 2 (High)

Fifty minutes into the test, the door and bypass were opened and the 7.00 lb/ft^3 load of small pieces were added. Four pieces of fuel were added that combined had a total fuel load weight was 13.3 pounds. The appliance door was immediately shut and the air settings remained fully open and the bypass was closed immediately. The appliance air setting was moved to fully closed at minute 101 when 58% (7.7 pounds) of the second fuel load had been consumed. This run missed the target range to change the air setting. While this change in air setting is out of range, it increases the amount of PM emitted during this run and lowers the amount of time it took to complete this phase. Based on review of the TEOM data the impact of this action likely increased the overall emission rate rather than reduced it. The second phase ended when 12.00 (90%) pounds of fuel was burned. Total time to complete Load 2 was 127 minutes, total elapsed test time 177 minutes. The coal bed weight at the end of the phase was 3.3 pounds. The overall HHV heating efficiency during this phase was 65.71%, the combustion efficiency was 99.50%, and the heat transfer efficiency was 66.04%. The heat input was 48,721 Btu/hr, and the heat output was 32,014 Btu/hr.

Load 3 (Medium/Maintenance)

One-hundred and seventy-seven minutes into the test the door was opened and two fuel pieces for the 5.00 lb/ft^3 load of large pieces were loaded into the appliance. The bypass was open for the fuel loading event. The door and bypass were closed immediately after loading the fuel. Air settings remained at low during this phase. The third phase ended when 8.5 (89%) pounds of fuel was burned. Total time to complete Load 3 was 135 minutes, total elapsed test time 312 minutes. The coal bed weight at the end of the phase was 4.3 pounds. The overall HHV heating efficiency during this phase was 73.99%, the combustion efficiency was 99.34%, and the heat transfer efficiency was 74.48%. The heat input was 38,335 Btu/hr, and the heat output was 28,362 Btu/hr.

Load 4 (Low)

Three-hundred and twelve minutes into the test, the appliance door was opened and the air settings set to fully open. The final fuel load consisting of three large pieces and three small pieces were placed in the appliance. The fuel loading density was 12.39 lb/ft^3. The bypass and door were closed immediately upon completing loading. Air settings were placed in the fully open position for the first eight minutes of the test phase. At minute 320 air settings were placed in the fully closed position. No fuel adjusts occurred during this phase. The fourth phase ended when 21.25 (90%) pounds of fuel was burned. Total time to

complete Load 4 was 307 minutes, total elapsed test time 619 minutes. The coal bed weight at the end of the phase was 6.6 pounds. The overall HHV heating efficiency during this phase was 70.09%, the combustion efficiency was 98.03%, and the heat transfer efficiency was 71.50%. The heat input was 37,384 Btu/hr, and the heat output was 26,203 Btu/hr.

Testing with Oak

Any technician notes made during the test run can be found in the text file log tab. The technician notes and test data summary form the narratives per test day below.

Oak Run #1

The first oak run was performed on April 3, 2019. The test was performed on Test Stand B.

Load 1-Start-Up

The startup fuel configuration used a top down fuel load configuration. L1, the startup load weighed 7.59 pounds – 1.9 pounds of kindling and 5.69 pounds of starter fuel. Fuel load density was 1.00 lb/ft^3 for kindling and 2.99 lb/ft^3 for starter fuel pieces. Emissions sampling began from a cold start ignition at 9:42. It took less than 60 seconds to ignite the fuel. The appliance door was cracked open one-inch, the bypass was open, and all air settings were fully open. The appliance door was closed at minute 6. Bypass was closed at minute 11. No poking, stirring events, or fuel adjustments were made during this phase of the test. The first phase ended when 5.59 pounds of fuel was burned. This left a coal bed weight of 2.0 pounds (74% of the fuel load, and 15% of the second load fuel weight). Total time to complete Load 1 was 57 minutes. The overall HHV heating efficiency during this phase was 59.82%, the combustion efficiency was 99.50%, and the heat transfer efficiency was 60.12%. The heat input was 55,590 Btu/hr, and heat output was 33,252 Btu/hr.

Load 2 (High)

Fifty-seven minutes into the test, the door and bypass were opened and the 7.00 lb/ft^3 load of small pieces were added. Three fuel pieces were added that combined had a total fuel load weight was 13.3 pounds. The appliance door was immediately shut and the air settings remained fully open and the bypass was closed immediately. The appliance air setting was moved to fully closed at minute 109 when 50% (6.7 pounds) of the second fuel load had been consumed. At minute 133 a fuel adjust was completed to maintain yellow flame. The second phase ended when 12.00 (90%) pounds of fuel was burned. Total time to complete Load 2 was 140 minutes, total elapsed test time 197 minutes. The coal bed weight at the end of the phase was 3.3 pounds. The overall HHV heating efficiency during this phase was 66.11%, the combustion efficiency was 98.44%, and the heat transfer efficiency was 67.16%. The heat input was 44,706 Btu/hr, and the heat output was 29,557 Btu/hr.

Load 3 (Medium/Maintenance)

One-hundred and ninety-seven minutes into the test the door was opened and two fuel pieces for the 4.98 lb/ft^3 load of large pieces were loaded into the appliance. The bypass was open for the fuel loading event. The door and bypass were closed immediately after loading the fuel. Air settings remained at low during this phase. A fuel adjust occurred at minute 285. The third phase ended when 8.57 (90%) pounds of fuel was burned. Total time to complete Load 3 was 155 minutes, total elapsed test time 352 minutes. The coal bed weight at the end of the phase was 4.2 pounds. The overall HHV heating efficiency during this phase was 71.97%, the combustion efficiency was 98.98%, and the heat transfer efficiency was 72.72%. The heat input was 33,381 Btu/hr, and the heat output was 24,026 Btu/hr.

Load 4 (Low)

Three-hundred and fifty-two minutes into the test, the appliance door was opened and the air settings set to fully open. The final fuel load consisting of three large pieces and three small pieces were placed in the appliance. The fuel loading density was 11.89 lb/ft^3. The bypass and door were closed immediately upon completing loading. Air settings were placed in the fully open position for the first ten minutes of the test phase. At minute 362 air settings were placed in the fully closed position. No fuel adjusts occurred during this phase. The fourth phase ended when 20.29 (90%) pounds of fuel was burned. Total time to complete Load 4 was 317 minutes, total elapsed test time 669 minutes. The coal bed weight at the end of the phase was 6.5 pounds. The overall HHV heating efficiency during this phase was 69.21%, the combustion efficiency was 97.35%, and the heat transfer efficiency was 71.09%. The heat input was 34,594 Btu/hr, and the heat output was 23,941 Btu/hr.

Oak Run #2

The second oak run was performed on April 4, 2019. The test was performed on Test Stand B.

Load 1-Start-Up

The startup fuel configuration used a top down fuel load configuration. L1, the startup load weighed 7.59 pounds – 1.9 pounds of kindling and 5.66 pounds of starter fuel. Fuel load density was 1.00 lb/ft^3 for kindling and 2.98 lb/ft^3 for starter fuel pieces. Emissions sampling began from a cold start ignition at 8:39. It took less than 60 seconds to ignite the fuel. The appliance door was cracked open one-inch, the bypass was open, and all air settings were fully open. The appliance door was closed at minute 5. Bypass was closed at minute 11. A fuel adjust occurred at minute 20, the bypass was opened, and the door cracked in order to obtain a yellow flame. At minute 25, the door was closed. At minute 35, the catalyst had reached the appropriate temperature to close the bypass and engage the catalyst. At minute 53, the fire required another fuel adjust. The first phase ended when 5.56 pounds of fuel was burned. This left a coal bed weight of 2.0 pounds (74% of the fuel load, and 15% of the second load fuel weight). Total time to complete Load 1 was 66 minutes. The overall HHV heating efficiency during this phase was 55.70%, the combustion efficiency was 97.53%, and the heat transfer efficiency was 56.88%. The heat input was 47,824 Btu/hr, and heat output was 26,640 Btu/hr.

Load 2 (High)

Sixty-six minutes into the test, the door and bypass were opened and the 7.00 lb/ft^3 load of small pieces were added. Three fuel pieces were added that combined had a total fuel load weight was 13.3 pounds. The appliance door was immediately shut and the air settings remained fully open and the bypass was closed immediately. The appliance air setting was moved to fully closed at minute 119 when 50% (6.7 pounds) of the second fuel load had been consumed. At minute 135, a fuel adjust was completed to maintain yellow flame. Another fuel adjust occurred at minute 161 due to lack of yellow flame. The second phase ended when 12.02 (90%) pounds of fuel was burned. Total time to complete Load 2 was 136 minutes, total elapsed test time 202 minutes. The coal bed weight at the end of the phase was 3.3 pounds. The overall HHV heating efficiency during this phase was 64.53%, the combustion efficiency was 98.23%, and the heat transfer efficiency was 65.69%. The heat input was 45,886 Btu/hr, and the heat output was 29,610 Btu/hr.

Load 3 (Medium/Maintenance)

Two-hundred and two minutes into the test the door was opened and two fuel pieces for the 4.96 lb/ft^3 load of large pieces were loaded into the appliance. The bypass was open for the fuel loading event. The door and bypass were closed immediately after loading the fuel. Air settings remained at low during this phase. A fuel adjust occurred at minute 270. The third phase ended when 8.53 (90%) pounds of fuel was burned. Total time to complete Load 3 was 175 minutes, total elapsed test time 377 minutes. The coal bed weight at the end of the phase was 4.2 pounds. The overall HHV heating efficiency during this phase was 70.83%, the combustion efficiency was 98.84%, and the heat transfer efficiency was 71.66%. The heat input was 29,335 Btu/hr, and the heat output was 20,779 Btu/hr.

Load 4 (Low)

Three-hundred and seventy-seven minutes into the test, the appliance door was opened and the air settings set to fully open. The final fuel load consisting of three large pieces and two small pieces were placed in the appliance. The fuel loading density was 11.98 lb/ft^3. The bypass and door were closed immediately upon completing loading. Air settings were placed in the fully open position for the first twelve minutes of the test phase. At minute 389 air settings were placed in the fully closed position. No fuel adjusts occurred during this phase. The fourth phase ended when 20.47 (90%) pounds of fuel was burned. Total time to complete Load 4 was 280 minutes, total elapsed test time 657 minutes. The coal bed weight at the end of the phase was 6.5 pounds. The overall HHV heating efficiency during this phase was 68.65%, the combustion efficiency was 96.81%, and the heat transfer efficiency was 70.91%. The heat input was 39,020 Btu/hr, and the heat output was 26,788 Btu/hr.

Oak Run #3

The third oak run was performed on April 5, 2019. The test was performed on Test Stand B.

Load 1-Start-Up

The startup fuel configuration used a top down fuel load configuration. L1, the startup load weighed 7.55 pounds – 1.88 pounds of kindling and 5.67 pounds of starter fuel. Fuel load density was 0.99 lb/ft^3 for kindling and 2.98 lb/ft^3 for starter fuel pieces. Emissions sampling began from a cold start ignition at 10:29. It took less than 60 seconds to ignite the fuel. The appliance door was cracked open one-inch, the bypass was open, and all air settings were fully open. The appliance door was closed at minute 5. Bypass was closed at minute 12. A fuel adjust occurred at minute 25, the bypass was opened, and the door cracked in order to obtain a yellow flame. At minute 31 another fuel adjust occurred to maintain yellow flame. The first phase ended when 5.55 pounds of fuel was burned. This left a coal bed weight of 2.0 pounds (74% of the fuel load, and 15% of the second load fuel weight). Total time to complete Load 1 was 56 minutes. The overall HHV heating efficiency during this phase was 62.03%, the combustion efficiency was 99.26%, and the heat transfer efficiency was 62.49%. The heat input was 56,278 Btu/hr, and heat output was 34,912 Btu/hr.

Load 2 (High)

Fifty-six minutes into the test, the door and bypass were opened and the 7.03 lb/ft^3 load of small pieces were added onto a coal bed that weighed 2.0 pounds. Three fuel pieces were added that combined had a total fuel load weight was 13.36 pounds. The appliance door was immediately shut and the air settings remained fully open and the bypass was closed immediately. The appliance air setting was moved to fully closed at minute 106 when 50% (6.7 pounds) of the second fuel load had been consumed. At minute 123, a fuel adjust was completed to maintain yellow flame. The second phase ended when 12.06 (90%) pounds of fuel was burned. Total time to complete Load 2 was 137 minutes, total elapsed test time 193 minutes. The coal bed weight at the end of the phase was 3.3 pounds. The overall HHV heating efficiency during this phase was 66.24%, the combustion efficiency was 98.58%, and the heat transfer efficiency was 67.2%. The heat input was 46,031 Btu/hr, and the heat output was 30,492 Btu/hr.

Load 3 (Medium/Maintenance)

One-hundred and ninety-three minutes into the test the door was opened and two fuel pieces for the 4.97 lb/ft^3 load of large pieces were loaded into the appliance. The bypass was open for the fuel loading event. The door and bypass were closed immediately after loading the fuel. Air settings remained at low during this phase. A fuel adjust occurred at minute 280 to maintain yellow flame. The third phase ended when 8.55 (90%) pounds of fuel was burned. Total time to complete Load 3 was 142 minutes, total elapsed test time 335 minutes. The coal bed weight at the end of the phase was 4.2 pounds. The overall HHV heating efficiency during this phase was 71.26%, the combustion efficiency was 98.78%, and the heat transfer efficiency was 72.15%. The heat input was 36,559 Btu/hr, and the heat output was 26,054 Btu/hr.

Load 4 (Low)

Three-hundred and thirty-five minutes into the test, the appliance door was opened and the air settings set to fully open. The final fuel load consisting of two large pieces and three small pieces were placed in the appliance. The fuel loading density was 12.04 lb/ft^3. The bypass and door were closed immediately upon completing loading. Air settings were placed in the fully open position for the first ten minutes of the test phase. At minute 345 air settings were placed in the fully closed position. No fuel adjusts occurred during this phase. The fourth phase ended when 20.57 (90%) pounds of fuel was burned. Total time to complete Load 4 was 303 minutes, total elapsed test time 638 minutes. The coal bed weight at the end of the phase was 6.5 pounds. The overall HHV heating efficiency during this phase was 69.61%, the combustion efficiency was 97.98%, and the heat transfer efficiency was 71.05%. The heat input was 36,434 Btu/hr, and the heat output was 25,362 Btu/hr.

ATTACHMENTS LIST

Attachment A – NYSERDA 2018 IDC Framework

Attachment B – NYSERDA 1400 TEOM SOP

Attachment C – NYSERDA 2019 Draft IDC Protocol

Attachment D – NYSERDA 1405 TEOM SOP

Attachment E – NYSERDA 2020 Draft IDC Protocol

Attachment F – HLS QAPP

Attachment G – Fuel Calculator V1 Data Outputs

Attachment H – HLS Lab Photos

Attachment I – Handwritten Lab Notes and Filter Weights